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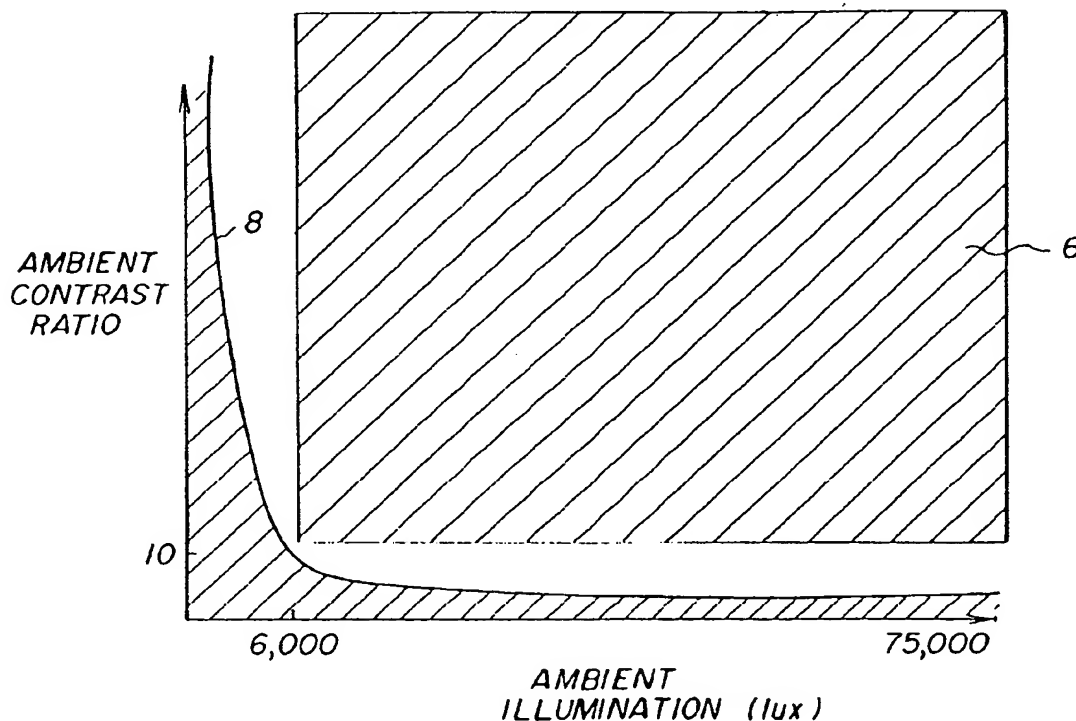
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(54) **Organic light emitting diode display**

(57) An OLED display having an ambient contrast ratio greater than ten at an ambient illumination greater than 6,000 lux at an average power of 100 milliwatts per centimeter squared.



**FIG. 1**

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## Description

[0001] The present invention relates to organic light emitting diode displays, and more particularly to their use in high-ambient illumination conditions.

[0002] Flat-panel displays of various sizes are used widely for many computing and communication applications. In particular, flat-panel displays are used in both indoor and outdoor applications under a wide variety of ambient lighting conditions. For adequate visibility displays require an ambient contrast ratio of at least three for viewing text and at least 10 for viewing images or graphics, where ambient contrast ratio (ACR) is defined as:

$$ACR = 1 + \frac{PDL}{ADR \times AI} \quad (1)$$

where PDL is the peak display luminance in lumens per meter squared; ADR is percent average display reflectance; and AI is the ambient illumination in lux.

[0003] Indoor applications experience relatively low levels of ambient illumination and require lower levels of display luminance to achieve the required ambient contrast ratio. Outdoor applications can experience relatively high levels of ambient illumination and may require higher levels of display luminance together with low display reflectance to achieve the required ambient contrast ratio. Moreover, most displays are preferably used in conditions of both high and low ambient illumination, from outdoor use during the day to nighttime use in a dark room.

[0004] Current illumination and display visibility standards cite 75,000 lux as a standard for outdoor ambient illumination on a bright and sunny day. Cloudy bright days have an ambient illumination of 16,000 lux and cloudy dull days have an ambient illumination of 6,000 lux. Indoor ambient illumination levels range from 0 to 1000 lux.

[0005] Conventional OLED displays have limited ambient contrast ratio and limited luminance. OLED displays have the problem that their ambient contrast ratio is greatly decreased when used in bright ambient illumination (due primarily to reflection of the ambient illumination from the face or substrate of the display). The luminance of an OLED display can be increased by increasing the current density flowing through the OLED light emissive materials, but doing so reduces the lifetime of the display, increases the power usage, and decreases the efficiency of the display. Moreover, at these higher currents, the power usage of the OLED displays is no longer competitive with back-lit LCD displays. It is known to use circular polarizers to increase the contrast of displays by reducing the reflection of ambient light from the display. Circular polarizers also decrease the light output from the display by about 60% while reducing the average display reflectance to 1.4%.

[0006] In an attempt to improve ambient contrast ratio

in OLED displays, US Patent 6,274,980 by Burrows et al. proposes to increase the luminance of an OLED device by stacking multiple OLED layers, all of which emit the same light and utilize the same OLED materials. The electrodes of the stacked units are held in common, thus effectively creating an OLED display element whose luminance is increased by the number of light emissive elements in the stack. However, this approach does not increase the efficiency of the display and the increased power usage of the display may not be competitive with alternative display technologies, such as LCDs.

[0007] A variety of techniques have been proposed to improve the efficiency of OLED and other thin-film displays. For example, diffraction gratings have been proposed to control the attributes of light emission from thin polymer films by inducing Bragg scattering of light that is guided laterally through the emissive layers ("Modification of polymer light emission by lateral microstructure", by Safonov, 2001, Synthetic Metals, 116, pp. 145-148 and "Bragg scattering from periodically microstructure light emitting diodes" by Lupton et al., November 20, 2000 in Applied Physics Letters, vol. 77 Number 21 pp. 3340-3342). Brightness enhancement films having diffractive properties and surface and volume diffusers are described in WO0237568 A1, by Chou et al., March 2, 2001.

[0008] The use of micro-cavities and scattering techniques are also known, see for example "Sharply Directed emission in organic electroluminescent diodes with an optical-micro-cavity structure" by Tsutsui, et al., October 10, 1994 in Applied Physics Letters 65, No. 15, pp. 1868-1870. However, these approaches still fail to meet the minimum ambient contrast ratio required for indoor and outdoor viewing.

[0009] It has been proposed to use a periodic, corrugated, grating structure to induce surface plasmon coupling for the light emitting layer in an organic luminescent device, thereby inhibiting lateral transmission and wave guiding of emitted light while increasing the efficiency and the light output of the structure. It is theoretically possible to couple up to 93% of the light emitted by the organic luminescent materials in an organic luminescent device. See Applied Physics Letter, Vol. 80, No. 20, entitled "Extraordinary transmission of organic photoluminescence through an otherwise opaque metal layer via surface plasmon cross coupling" by Gifford et al., May 20, 2002. Gifford et al. disclose creating the grating geometry for photoluminescent surface plasmon coupling by exposing a photoresist on glass with an interferometric pattern, followed by depositing subsequent layers that replicate the underlying surface profile. This approach is not compatible with the current manufacturing techniques used to make active matrix OLED displays, since for top emitting OLED display devices, a layer of thin film transistors are formed on the substrate prior to forming the OLEDs. For bottom emitting OLED displays, manufacturing starts with a glass substrate that is coated with a layer of conductive indium tin

oxide (ITO) that is patterned to provide conductors for thin film transistors located on the substrate. The use of photoresist to create plasmon inducing gratings is problematical because the photoresist is an electrical insulator, thereby isolating the underlying ITO conductors from the OLED materials. Gifford et al. also suggest that the use of surface plasmon coupling can be an efficient means for outcoupling electroluminescence in an OLED device by using shadow masks on any desirable substrate. The use of shadow masks is not practical to create the gratings because of the small dimensions of the gratings. They also disclose that they have fabricated an OLED that uses surface plasmon coupling on a silicon substrate, but silicon substrates are not conventional or practical for OLED display devices.

[0010] There is a need therefore for an improved OLED display that avoids the problems noted above, while providing a minimum ambient contrast ratio for both indoor and outdoor viewing.

[0011] The need is met according to the present invention by providing an OLED display having an ambient contrast ratio greater than ten at an ambient illumination greater than 6,000 lux at an average power of 100 milliwatts per centimeter squared.

Fig. 1 is a graph showing the operating region of a display according to the present invention;

Fig. 2 is a schematic partial cross sectional view of a prior art top emitting OLED display;

Fig. 3 is a schematic partial cross sectional view of a top emitting OLED display according to the present invention;

Fig. 4. is a schematic partial cross sectional view of a prior art bottom emitting OLED display;

Fig. 5. a schematic partial cross sectional view of a bottom emitting OLED display according to the present invention;

Fig. 6 is schematic partial cross sectional view of a stacked top emitting OLED display according to the present invention; and

Fig. 7 is a schematic cross sectional diagram of a prior art OLED.

[0012] An OLED display according to the present invention has an ambient contrast ratio greater than ten in an ambient illumination greater than 6,000 lux at an average power of 100 milliwatts or less per square centimeter of display area. Referring to Fig. 1, the shaded area of the graph labeled 6 represents the operating ranges of display devices according to the present invention. Prior art OLED display devices operate in the range labeled 8.

[0013] Referring to Fig. 2, a prior art top-emitting OLED display device 10 includes a substrate 12, and a thin-film transistor (TFT) active matrix layer 14 comprising an array of TFTs that provides power to OLED elements. A patterned first insulating layer 16 is provided over the TFT active matrix layer, and an array of first

electrodes 18 are provided over a planarized insulating layer 16 and in electrical contact with the TFT active matrix layer. A patterned second insulating layer 17 is provided over the array of first electrodes 18 such that at least a portion of the each of the first electrodes 18 is exposed.

[0014] Over the first electrodes and insulating layers are provided red, green, and blue-emitting organic OLED elements, 19R, 19G, and 19B, respectively, which are referred to collectively as the OLED layer 19. These elements are composed of further layers as described in more detail below. Herein, the collection of OLED elements, including hole injection, hole transport, and electron transport layers may also be referred to as the OLED layer 19. The light-emitting area is generally defined by the area of the first electrode 18 in contact with the OLED elements. Over the OLED layer 19 is provided a transparent, common second electrode 30 that has sufficient optical transparency to allow transmission of the generated red, green, and blue light. An optional second electrode protection layer 32 may be provided to protect the electrode and underlying layers. Each first electrode in combination with its associated OLED element and second electrode is herein referred to as an OLED. A typical top-emitting OLED display device comprises an array of OLEDs wherein each OLED emits red, green or blue. A gap, generally filled with inert gas or a transmissive polymer material separates the electrode protection layer from an encapsulating cover 36. The encapsulating cover 36 may also be a layer deposited directly on the common second electrode 30 or the optional second electrode protection layer 32. Details of the OLED materials, layers, and architecture are described in more detail below. A circular polarizer 38 is provided over the device to increase the ambient contrast ratio by decreasing the average display reflectance.

[0015] In operation, the thin-film transistors in TFT layer 14 control current between the first electrodes 18, each of which can be selectively addressed, and the common second electrode 30. Holes and electrons recombine within the OLED elements to emit light 24 R, G and B, referred to herein as emitted light 24 from the light emitting elements 19 R, G and B respectively. Because the layers are so thin, typically several hundred angstroms, they are largely transparent. Prior art top emitting OLED displays have fill factors of approximately 60 percent. The term fill factor refers to the percentage of the total display surface area that is light emissive. Theoretical calculations show that such a prior art top emitting display is typically capable of providing an ambient contrast ratio of 8.5 in an ambient illumination of 6,000 lux when driven at 100 milliwatts per square centimeter. Driving a display at 100 milliwatts per square centimeter provides a power usage that is competitive with other existing flat panel display technologies such as back-lit liquid crystal and plasma displays.

[0016] Referring to Fig. 3, a top emitting embodiment

of a display according to the present invention includes a substrate **12**, TFT layer **14**, an insulating layer **16**, first patterned electrode **18**, and second insulating layer **17**. Conventional OLED layers **19** are deposited upon the insulating layer **17** and first patterned metal electrodes **18**. A second, common electrode **30** and protection layer **32** are deposited above the OLED layers **19**. The display **10** is encapsulated with an encapsulating cover or layer **36**.

**[0017]** The insulating layer **16** is not a conventional planarization layer as in the prior art but rather has a periodic physical grating structure that makes the layer thicker in some locations and thinner in others. The size and period of the grating structure is selected to be effective to cause surface plasmon cross coupling in overlying metallic layers that conform to the grating structure. In particular, the first patterned metal electrode **18** has a similar periodic structure, as do the OLED layers **19**. The second electrode layer **30** is likewise conformable to the grating structure, but the top surface of the second electrode layer **30** or layers above the second electrode **30** may, or may not, conform to the periodic grating structure.

**[0018]** In a preferred embodiment, the periodic grating structure of the insulating layer **16** differs for each of the red, green, and blue OLED light emitting areas **19R**, **19G**, and **19B** respectively. The period of the grating structure is centered on the frequency of light emitted by the OLED materials. For example, the periodic structure of the insulating layer **16** can have a period ranging from 200 to 1000 nm. The height of the physical structure is about 100 nm although larger or smaller heights are possible; the minimum thickness of the insulating layer must be sufficient to provide good insulation between the first patterned metal electrode **18** and the thin-film electronics devices **14**. The period and heights of the periodic grating structure affect the frequency of optimum cross-coupling and angular dependence. In general, the OLED element layer should be as thin as possible to cause as much energy as possible to undergo surface plasmon cross coupling in the metallic layers. The insulating layer **16** may be reflective or transmissive, or may be opaque to increase the contrast of the device. The insulating layer **16** is made by conventional means, for example photolithography.

**[0019]** In operation, current is passed via the electrodes **18** and **30** through the light emitting elements **19** causing light to be emitted both upward through second electrode **30** and downward toward the substrate **12**. The periodic structure of metal electrodes **18** and/or **30** and the OLED layer **19** causes surface plasmon cross coupling between the layers. The surface plasmon effect has the additional benefit of reducing the absorption of light in the electrode, further increasing the light output from the device. The emission from the OLED device is no longer Lambertian, but is highly directional along an axis perpendicular to the display. The light emitted forward is seen by a viewer. The light emitted backward

is either absorbed or reflected by the insulating layer. Theoretical calculations show that a top emitting OLED device having surface plasmon coupling and a circular polarizer as described above is capable of producing an ambient contrast ratio of 38.4 at 6,000 lux when driven at 100 milliwatts per square centimeter. It is also capable of producing an ambient contrast ratio greater than ten at an ambient illumination greater than 24,000 lux.

**[0020]** The present invention may be applied to both a top-emitter (wherein light is emitted through the cover as described above) or a bottom-emitter (wherein light is emitted through the substrate). In the bottom emitter case, the periodic grating structure may be created directly upon the substrate **12**, or in insulating or conducting layers applied to the substrate. Referring to Fig. 4, a prior art bottom-emitter OLED device uses a patterned conductive layer **13** of indium tin oxide (ITO) deposited on the substrate to conduct current to the light emitting areas and thin-film transistors. The remainder of the layers are the same as in the top-emitting device described with reference to Fig. 2. Prior art bottom emitting displays have fill factors of 30 percent. Because of the lower fill factor, the OLED pixels will be driven at a higher current density than the top emitting display to achieve the same ambient contrast ratio at the same power per unit area of the display, thereby reducing the lifetime of the display.

**[0021]** Referring to Fig. 5, in a bottom-emitter OLED display according to the present invention, the ITO layer **13** is provided with a periodic grating pattern similar to that of the insulating layer **16** of the top emitter in the areas where light is emitted. The grating pattern is created in the ITO layer **13** using well-known photolithography techniques. A thin metal electrode layer **15** is deposited on the ITO layer, the organic materials are conformably deposited on the metal layer, and the remainder of the depositions are as described above. The thin metal electrode **15** may be omitted, but surface plasmon coupling will not be supported in the ITO layer alone. Because of the lower fill factor, the OLED pixels will be driven at a higher current density than the top emitting display to achieve the same ambient contrast ratio at the same power per unit area of the display, thereby reducing the lifetime of the display.

**[0022]** Because the emitted light **24** has an angular dependence on frequency, a diffuser (not shown) may be included in the display **10** to mitigate the effect of color aberrations. This diffuser may be applied to the exterior of the device, for example, or the diffuser may be incorporated into the cover **36** (of a top emitting device) or the substrate **12** (of a bottom emitting device).

**[0023]** In an alternative embodiment of the present invention, the period of the structure of the insulating layer **16** and conformable layers deposited upon it may be constant across the device rather than different for each individual color **19R**, **G**, and **B**. This simplifies the construction of the device with some loss in efficiency of the

light output and angular dependence of frequency.

[0024] In an alternative embodiment of the present invention, instead of using a circular polarizer to reduce the display reflectance, a light absorbing layer may be employed under the OLED materials to increase the ambient contrast ratio.

[0025] The present invention may also be employed with stacked OLEDs as described in US 6,274,980, referenced above. The stacked OLEDs has the effect of increasing the fill factor of the display, thereby increasing the lifetime for a given display luminance and power per unit area of the display.

[0026] Referring to Fig. 6, a top-emitting, stacked OLED display device is shown. In operation, current is passed via the electrodes 18 and 30 through the OLED layer 19 causing light to be emitted both upward through second electrode 30 and downward toward the substrate. The periodic structure of the OLED layer 19 and electrodes causes surface plasmon coupling to the emissive layers above and below. This causes the light to be emitted orthogonally to the plane of the organic materials rather than in a Lambertian distribution. The light emitted toward the back of the device will be absorbed by the black body absorber. Light emitted forward will be directed out of the device, passing through the transparent electrodes 30, protective layer 32, and the encapsulating cover 36. Although Fig. 6 illustrates a stack of three OLEDs, a greater or smaller number of OLEDs may be utilized with a consequent increase or decrease in light output. The stacked OLED configuration can be used with both top and bottom-emitting OLED display devices.

[0027] In a high ambient light environment, considerable energy is absorbed by the display, which can become quite hot. This heat is deleterious to the OLED materials. Provision of a heat conductive substrate (for a top emitter) or a heat conductive encapsulating cover (for a bottom emitter) can reduce local heating within the device and dissipate the heat to the environment. Heat conduction and dissipation can be enhanced by the use of cooling devices on the display; for example, cooling fins or active cooling devices such as fans, heat pipes, etc., can be employed to cool the display.

[0028] Details of the OLED materials, layers, and architecture are described in more detail below.

[0029] The present invention can be employed in most OLED device configurations. These include very simple structures comprising a single anode and cathode to more complex devices, such as passive matrix displays comprised of orthogonal arrays of anodes and cathodes to form pixels, and active-matrix displays where each pixel is controlled independently, for example, with thin-film transistors (TFTs).

[0030] There are numerous configurations of the organic layers wherein the present invention can be successfully practiced. A typical structure is shown in Fig. 7 and is comprised of a substrate 12, an anode 103, a hole-injecting layer 105, a hole-transporting layer 107,

a light-emitting layer 109, an electron-transporting layer 111, and a cathode 113. These layers are described in detail below. Note that the substrate may alternatively be located adjacent to the cathode, or the substrate may actually constitute the anode or cathode. The organic layers between the anode and cathode are conveniently referred to as the organic EL element. The total combined thickness of the organic layers is preferably less than 500 nm.

[0031] The anode and cathode of the OLED are connected to a voltage/current source 250 through electrical conductors 260. The OLED is operated by applying a potential between the anode and cathode such that the anode is at a more positive potential than the cathode. Holes are injected into the organic EL element from the anode and electrons are injected into the organic EL element at the cathode. Enhanced device stability can sometimes be achieved when the OLED is operated in an AC mode where, for some time period in the cycle, the potential bias is reversed and no current flows. An example of an AC driven OLED is described in US 5,552,678.

[0032] The OLED device of this invention is typically provided over a supporting substrate where either the cathode or anode can be in contact with the substrate. The electrode in contact with the substrate is conveniently referred to as the bottom electrode. Conventionally, the bottom electrode is the anode, but this invention is not limited to that configuration. The substrate can either be light transmissive or opaque, depending on the intended direction of light emission. The light transmissive property is desirable for viewing the EL emission through the substrate. Transparent glass or plastic is commonly employed in such cases. For applications where the EL emission is viewed through the top electrode, the transmissive characteristic of the bottom support is immaterial, and therefore can be light transmissive, light absorbing or light reflective. Substrates for use in this case include, but are not limited to, glass, plastic, semiconductor materials, silicon, ceramics, and circuit board materials. Of course it is necessary to provide in these device configurations a light-transparent top electrode.

[0033] When EL emission is viewed through anode 103, the anode should be transparent or substantially transparent to the emission of interest. Common transparent anode materials used in this invention are indium-tin oxide (ITO), indium-zinc oxide (IZO) and tin oxide, but other metal oxides can work including, but not limited to, aluminum- or indium-doped zinc oxide, magnesium-indium oxide, and nickel-tungsten oxide. In addition to these oxides, metal nitrides, such as gallium nitride, and metal selenides, such as zinc selenide, and metal sulfides, such as zinc sulfide, can be used as the anode. For applications where EL emission is viewed only through the cathode electrode, the transmissive characteristics of anode are immaterial and any conductive material can be used, transparent, opaque or reflective.

tive. Example conductors for this application include, but are not limited to, gold, iridium, molybdenum, palladium, and platinum. Typical anode materials, transmissive or otherwise, have a work function of 4.1 eV or greater. Desired anode materials are commonly deposited by any suitable means such as evaporation, sputtering, chemical vapor deposition, or electrochemical means. Anodes can be patterned using well-known photolithographic processes. Optionally, anodes may be polished prior to application of other layers to reduce surface roughness so as to minimize shorts or enhance reflectivity.

**[0034]** While not always necessary, it is often useful to provide a hole-injecting layer **105** between anode **103** and hole-transporting layer **107**. The hole-injecting material can serve to improve the film formation property of subsequent organic layers and to facilitate injection of holes into the hole-transporting layer. Suitable materials for use in the hole-injecting layer include, but are not limited to, porphyrinic compounds as described in US 4,720,432, plasma-deposited fluorocarbon polymers as described in US 6,208,075, and some aromatic amines, for example, *m*-MTDATA (4,4',4''-tris[(3-methylphenyl)phenylamino]triphenylamine). Alternative hole-injecting materials reportedly useful in organic EL devices are described in EP 0 891 121 A1 and EP 1 029 909 A1.

**[0035]** The hole-transporting layer **107** contains at least one hole-transporting compound such as an aromatic tertiary amine, where the latter is understood to be a compound containing at least one trivalent nitrogen atom that is bonded only to carbon atoms, at least one of which is a member of an aromatic ring. In one form the aromatic tertiary amine can be an arylamine, such as a monoarylamine, diarylamine, triarylamine, or a polymeric arylamine. Exemplary monomeric triarylaminos are illustrated by Klupfel et al. in US 3,180,730. Other suitable triarylaminos substituted with one or more vinyl radicals and/or comprising at least one active hydrogen containing group are disclosed by Brantley et al. US 3,567,450 and 3,658,520.

**[0036]** A more preferred class of aromatic tertiary amines are those which include at least two aromatic tertiary amine moieties as described in US 4,720,432 and 5,061,569. The hole-transporting layer can be formed of a single or a mixture of aromatic tertiary amine compounds. Illustrative of useful aromatic tertiary amines are the following:

1,1-Bis(4-di-*p*-tolylaminophenyl)cyclohexane  
 1,1-Bis(4-di-*p*-tolylaminophenyl)-4-phenylcyclohexane  
 4,4'-Bis(diphenylamino)quadruphenyl  
 Bis(4-dimethylamino-2-methylphenyl)-phenylmethane  
 N,N,N-Tri(*p*-tolyl)amine  
 4-(di-*p*-tolylamino)-4'-[4(di-*p*-tolylamino)-styryl]stilbene

N,N,N',N'-Tetra-*p*-tolyl-4,4'-diaminobiphenyl  
 N,N,N',N'-Tetraphenyl-4,4'-diaminobiphenyl  
 N,N,N',N'-tetra-1-naphthyl-4,4'-diaminobiphenyl  
 N,N,N',N'-tetra-2-naphthyl-4,4'-diaminobiphenyl  
 N-Phenylcarbazole  
 4,4'-Bis[N-(1-naphthyl)-N-phenylamino]biphenyl  
 4,4'-Bis[N-(1-naphthyl)-N-(2-naphthyl)amino]biphenyl  
 4,4'-Bis[N-(1-naphthyl)-N-phenylamino]*p*-terphenyl  
 4,4'-Bis[N-(2-naphthyl)-N-phenylamino]biphenyl  
 4,4'-Bis[N-(3-acenaphthenyl)-N-phenylamino]biphenyl  
 1,5-Bis[N-(1-naphthyl)-N-phenylamino]naphthalene  
 4,4'-Bis[N-(9-anthryl)-N-phenylamino]biphenyl  
 4,4'-Bis[N-(1-anthryl)-N-phenylamino]*p*-terphenyl  
 4,4'-Bis[N-(2-phenanthryl)-N-phenylamino]biphenyl  
 4,4'-Bis[N-(8-fluoranthryl)-N-phenylamino]biphenyl  
 4,4'-Bis[N-(2-pyrenyl)-N-phenylamino]biphenyl  
 4,4'-Bis[N-(2-naphthacenyl)-N-phenylamino]biphenyl  
 4,4'-Bis[N-(2-perylenyl)-N-phenylamino]biphenyl  
 4,4'-Bis[N-(coroneryl)-N-phenylamino]biphenyl  
 2,6-Bis(di-*p*-tolylamino)naphthalene  
 2,6-Bis[di-(1-naphthyl)amino]naphthalene  
 2,6-Bis[N-(1-naphthyl)-N-(2-naphthyl)amino]naphthalene  
 N,N,N',N'-Tetra(2-naphthyl)-4,4'-diamino-*p*-terphenyl  
 4,4'-Bis[N-phenyl-N-[4-(1-naphthyl)-phenyl]amino]biphenyl  
 4,4'-Bis[N-phenyl-N-(2-pyrenyl)amino]biphenyl  
 2,6-Bis[N,N-di(2-naphthyl)amine]fluorene  
 1,5-Bis[N-(1-naphthyl)-N-phenylamino]naphthalene  
 4,4',4''-tris[(3-methylphenyl)phenylamino]triphenylamine

**[0037]** Another class of useful hole-transporting materials includes polycyclic aromatic compounds as described in EP 1 009 041. Tertiary aromatic amines with more than two amine groups may be used including oligomeric materials. In addition, polymeric hole-transporting materials can be used such as poly(N-vinylcarbazole) (PVK), polythiophenes, polypyrrole, polyaniline, and copolymers such as poly(3,4-ethylenedioxythiophene) / poly(4-styrenesulfonate) also called PEDOT/PSS.

**[0038]** As more fully described in US 4,769,292 and 5,935,721, the light-emitting layer (LEL) **109** of the organic EL element includes a luminescent or fluorescent material where electroluminescence is produced as a result of electron-hole pair recombination in this region. The light-emitting layer can be comprised of a single material, but more commonly consists of a host material

doped with a guest compound or compounds where light emission comes primarily from the dopant and can be of any color. The host materials in the light-emitting layer can be an electron-transporting material, as defined below, a hole-transporting material, as defined above, or another material or combination of materials that support hole-electron recombination. The dopant is usually chosen from highly fluorescent dyes, but phosphorescent compounds, e.g., transition metal complexes as described in WO 98/55561, WO 00/18851, WO 00/57676, and WO 00/70655 are also useful. Dopants are typically coated as 0.01 to 10 % by weight into the host material. Polymeric materials such as polyfluorenes and polyvinylarylenes (e.g., poly(p-phenylenevinylene). PPV) can also be used as the host material. In this case, small molecule dopants can be molecularly dispersed into the polymeric host, or the dopant could be added by copolymerizing a minor constituent into the host polymer.

**[0039]** An important relationship for choosing a dye as a dopant is a comparison of the bandgap potential which is defined as the energy difference between the highest occupied molecular orbital and the lowest unoccupied molecular orbital of the molecule. For efficient energy transfer from the host to the dopant molecule, a necessary condition is that the band gap of the dopant is smaller than that of the host material. For phosphorescent emitters it is also important that the host triplet energy level of the host be high enough to enable energy transfer from host to dopant.

**[0040]** Host and emitting molecules known to be of use include, but are not limited to, those disclosed in US 4,769,292; 5,141,671; 5,150,006; 5,151,629; 5,405,709; 5,484,922; 5,593,788; 5,645,948; 5,683,823; 5,755,999; 5,928,802; 5,935,720; 5,935,721; and 6,020,078.

**[0041]** Metal complexes of 8-hydroxyquinoline (oxine) and similar derivatives constitute one class of useful host compounds capable of supporting electroluminescence. Illustrative of useful chelated oxinoid compounds are the following:

CO-1: Aluminum trisoxine [alias, tris(8-quinolinolato)aluminum(III)]

CO-2: Magnesium bisoxine [alias, bis(8-quinolinolato)magnesium(II)]

CO-3: Bis[benzo(f)-8-quinolinolato]zinc (II)

CO-4: Bis(2-methyl-8-quinolinolato)aluminum(III)-μ-oxo-bis(2-methyl-8-quinolinolato) aluminum(III)

CO-5: Indium trisoxine [alias, tris(8-quinolinolato)indium]

CO-6: Aluminum tris(5-methyloxine) [alias, tris(5-methyl-8-quinolinolato) aluminum(III)]

CO-7: Lithium oxine [alias, (8-quinolinolato)lithium (I)]

CO-8: Gallium oxine [alias, tris(8-quinolinolato)gallium(III)]

CO-9: Zirconium oxine [alias, tetra(8-quinolinolato)

zirconium(IV)]

**[0042]** Other classes of useful host materials include, but are not limited to: derivatives of anthracene, such as 9,10-di-(2-naphthyl)anthracene and derivatives thereof as described in US 5,935,721, distyrylarylene derivatives as described in US 5,121,029, and benzazole derivatives, for example, 2, 2', 2''-(1,3,5-phenylene)tris [1-phenyl-1H-benzimidazole]. Carbazole derivatives are particularly useful hosts for phosphorescent emitters.

**[0043]** Useful fluorescent dopants include, but are not limited to, derivatives of anthracene, tetracene, xanthene, perylene, rubrene, coumarin, rhodamine, and quinacridone, dicyanomethylenepyrans compounds, thiopyran compounds, polymethine compounds, pyrilium and thiapyrilium compounds, fluorene derivatives, perfluoranthene derivatives, indenoperylene derivatives, bis(aziryl)amine boron compounds, bis(aziryl)methane compounds, and carbostyryl compounds.

**[0044]** Preferred thin-film-forming materials for use in forming the electron-transporting layer 111 of the organic EL elements of this invention are metal chelated oxinoid compounds, including chelates of oxine itself (also commonly referred to as 8-quinolinol or 8-hydroxyquinoline). Such compounds help to inject and transport electrons, exhibit high levels of performance, and are readily fabricated in the form of thin-films. Exemplary oxinoid compounds were listed previously.

**[0045]** Other electron-transporting materials include various butadiene derivatives as disclosed in US 4,356,429 and various heterocyclic optical brighteners as described in US 4,539,507. Benzazoles and triazines are also useful electron-transporting materials.

**[0046]** When light emission is viewed solely through the anode, the cathode 113 used in this invention can be comprised of nearly any conductive material. Desirable materials have good film-forming properties to ensure good contact with the underlying organic layer, promote electron injection at low voltage, and have good stability. Useful cathode materials often contain a low work function metal (< 4.0 eV) or metal alloy. One preferred cathode material is comprised of a Mg:Ag alloy wherein the percentage of silver is in the range of 1 to 20 %, as described in US 4,885,221. Another suitable class of cathode materials includes bilayers comprising a thin electron-injection layer (EIL) in contact with the organic layer (e.g., ETL) which is capped with a thicker layer of a conductive metal. Here, the EIL preferably includes a low work function metal or metal salt, and if so, the thicker capping layer does not need to have a low work function. One such cathode is comprised of a thin layer of LiF followed by a thicker layer of Al as described in US 5,677,572. Other useful cathode material sets include, but are not limited to, those disclosed in US 5,059,861; 5,059,862, and 6,140,763.

**[0047]** When light emission is viewed through the cathode, the cathode must be transparent or nearly



transparent. For such applications, metals must be thin or one must use transparent conductive oxides, or a combination of these materials. Optically transparent cathodes have been described in more detail in US 4,885,211, US 5,247,190, JP 3,234,963, US 5,703,436, US 5,608,287, US 5,837,391, US 5,677,572, US 5,776,622, US 5,776,623, US 5,714,838, US 5,969,474, US 5,739,545, US 5,981,306, US 6,137,223, US 6,140,763, US 6,172,459, EP 1 076 368, US 6,278,236, and US 6,284,393. Cathode materials are typically deposited by evaporation, sputtering, or chemical vapor deposition. When needed, patterning can be achieved through many well known methods including, but not limited to, through-mask deposition, integral shadow masking, for example, as described in US 5,276,380 and EP 0 732 868, laser ablation, and selective chemical vapor deposition.

**[0048]** In some instances, layers 109 and 111 can optionally be collapsed into a single layer that serves the function of supporting both light emission and electron transportation. It also known in the art that emitting dopants may be added to the hole-transporting layer, which may serve as a host. Multiple dopants may be added to one or more layers in order to create a white-emitting OLED, for example, by combining blue- and yellow-emitting materials, cyan- and red-emitting materials, or red-, green-, and blue-emitting materials. White-emitting devices are described, for example, in EP 1 187 235, US 20020025419, EP 1 182 244, US 5,683,823, US 5,503,910, US 5,405,709, and US 5,283,182.

**[0049]** Additional layers such as electron or hole-blocking layers as taught in the art may be employed in devices of this invention. Hole-blocking layers are commonly used to improve efficiency of phosphorescent emitter devices, for example, as in US 20020015859.

**[0050]** This invention may be used in so-called stacked device architecture, for example, as taught in US 5,703,436 and US 6,337,492.

**[0051]** The organic materials mentioned above are suitably deposited through a vapor-phase method such as sublimation, but can be deposited from a fluid, for example, from a solvent with an optional binder to improve film formation. If the material is a polymer, solvent deposition is useful but other methods can be used, such as sputtering or thermal transfer from a donor sheet. The material to be deposited by sublimation can be vaporized from a sublimator "boat" often comprised of a tantalum material, e.g., as described in US 6,237,529, or can be first coated onto a donor sheet and then sublimed in closer proximity to the substrate. Layers with a mixture of materials can utilize separate sublimator boats or the materials can be pre-mixed and coated from a single boat or donor sheet. Patterned deposition can be achieved using shadow masks, integral shadow masks (US 5,294,870), spatially-defined thermal dye transfer from a donor sheet (US 5,688,551, 5,851,709 and 6,066,357) and inkjet method (US 6,066,357).

**[0052]** Most OLED devices are sensitive to moisture or oxygen, or both, so they are commonly sealed in an inert atmosphere such as nitrogen or argon, along with a desiccant such as alumina, bauxite, calcium sulfate, clays, silica gel, zeolites, alkaline metal oxides, alkaline earth metal oxides, sulfates, or metal halides and perchlorates. Methods for encapsulation and desiccation include, but are not limited to, those described in US 6,226,890. In addition, barrier layers such as SiO<sub>x</sub>, Te-flon, and alternating inorganic/polymeric layers are known in the art for encapsulation.

**[0053]** OLED devices of this invention can employ various well-known optical effects in order to enhance its properties if desired. This includes optimizing layer thicknesses to yield maximum light transmission, providing dielectric mirror structures, replacing reflective electrodes with light-absorbing electrodes, providing anti glare or anti-reflection coatings over the display, providing a polarizing medium over the display, or providing colored, neutral density, or color conversion filters over the display. Filters, polarizers, and anti-glare or anti-reflection coatings may be specifically provided over the cover or as part of the cover.

**[0054]** The entire contents of the patents and other publications referred to in this specification are incorporated herein by reference.

#### Claims

1. An OLED display having an ambient contrast ratio greater than ten at an ambient illumination greater than 6,000 lux at an average power of 100 milliwatts per centimeter squared.
2. The OLED display claimed in claim 1, comprising an array of OLEDs having one or more metallic electrodes that define a periodic grating structure capable of supporting surface plasmon outcoupling of light from the OLEDs.
3. The OLED display claimed in claim 1, wherein the OLED display is a top-emitting display.
4. The OLED display claimed in claim 1, wherein the OLED display is a bottom emitting display.
5. The OLED display claimed in claim 1, wherein the OLED display comprises an array of stacked OLEDs.
6. The OLED display claimed in claim 1, including a light diffuser located over the display.
7. The OLED display claimed in claim 1, including means for reducing display reflectance.
8. The OLED display claimed in claim 7, wherein the



means for reducing display reflectance is a circular polarizer located over the display.

9. The OLED display claimed in claim 7, wherein the means for reducing display reflectance is a light absorbing layer. 5
10. The OLED display claimed in claim 7, including cooling means for removing heat generated by absorbed ambient illumination. 10
11. The OLED display claimed in claim 10, wherein the cooling means comprises a conductive substrate or encapsulating cover. 15
12. The OLED display claimed in claim 10, wherein the cooling means comprises a heat sink located on the back of the display.
13. The OLED display claimed in claim 1, having an ambient contrast ratio greater than ten at an ambient illumination greater than 24,000 lux. 20

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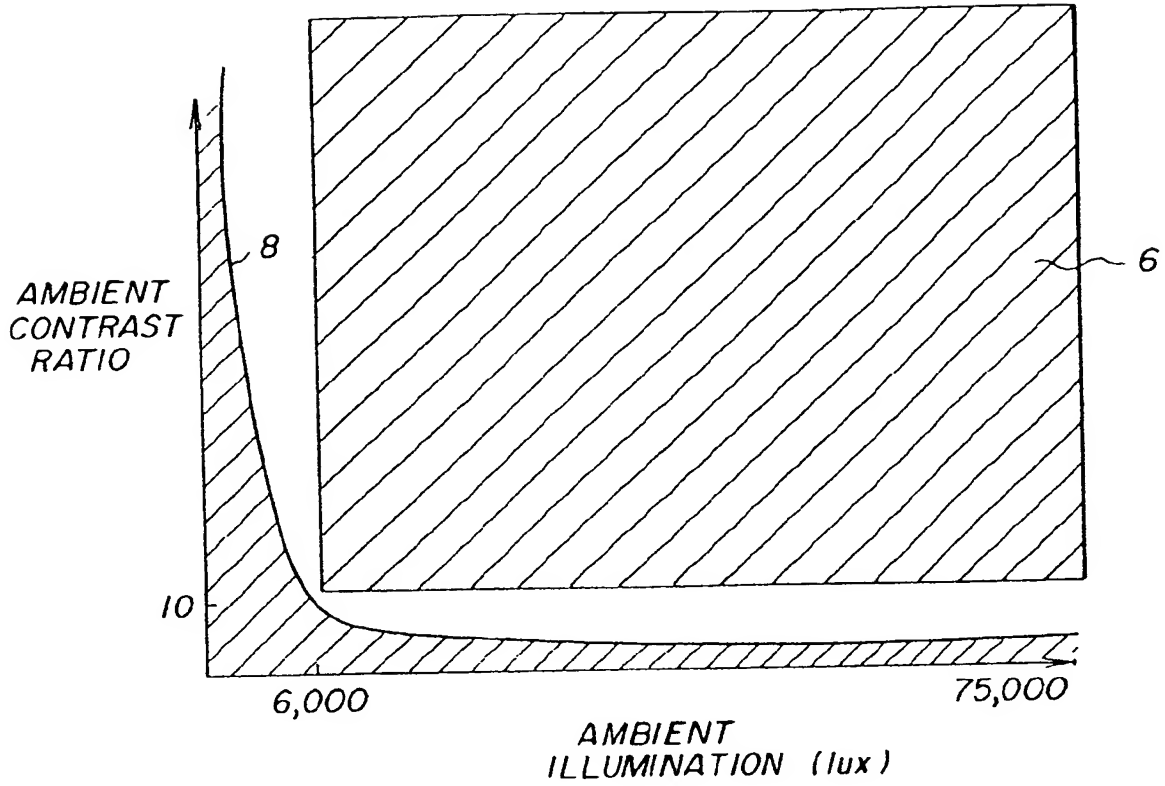


FIG. 1

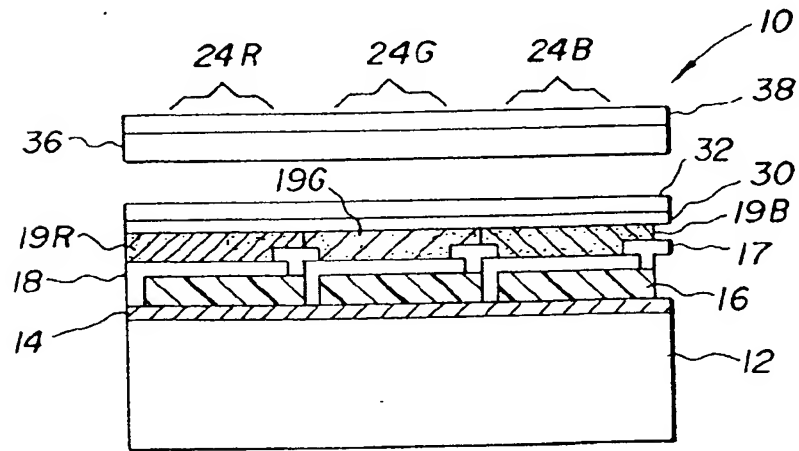


FIG. 2

PRIOR ART

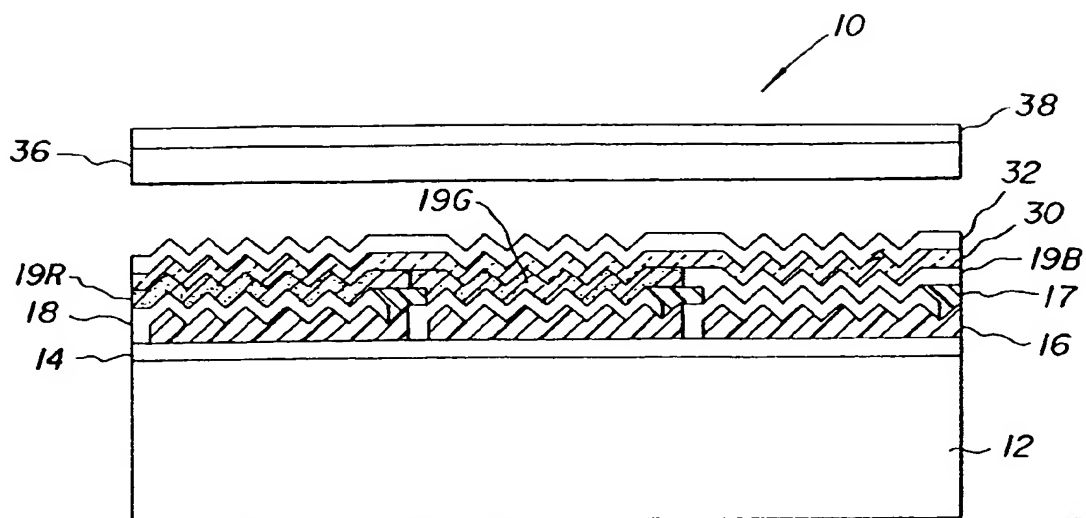


FIG. 3

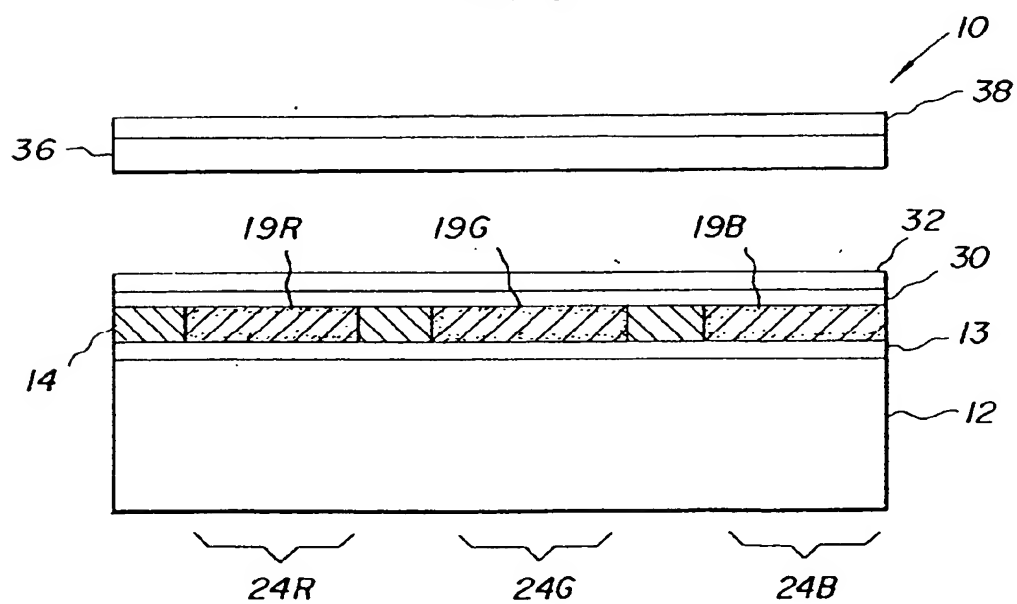


FIG. 4  
PRIOR ART

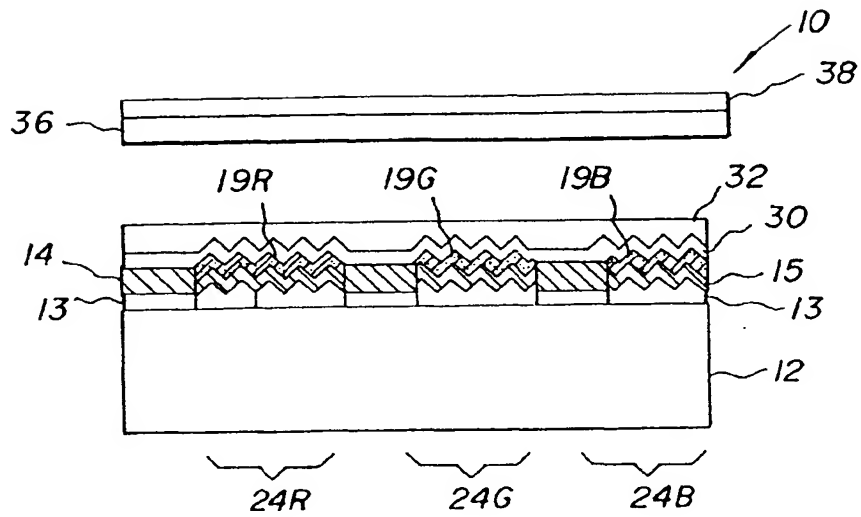


FIG. 5

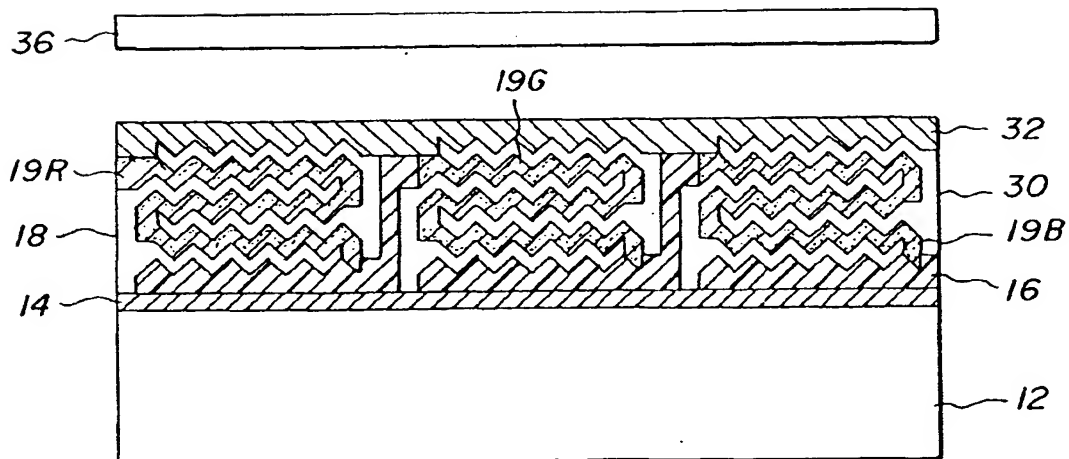
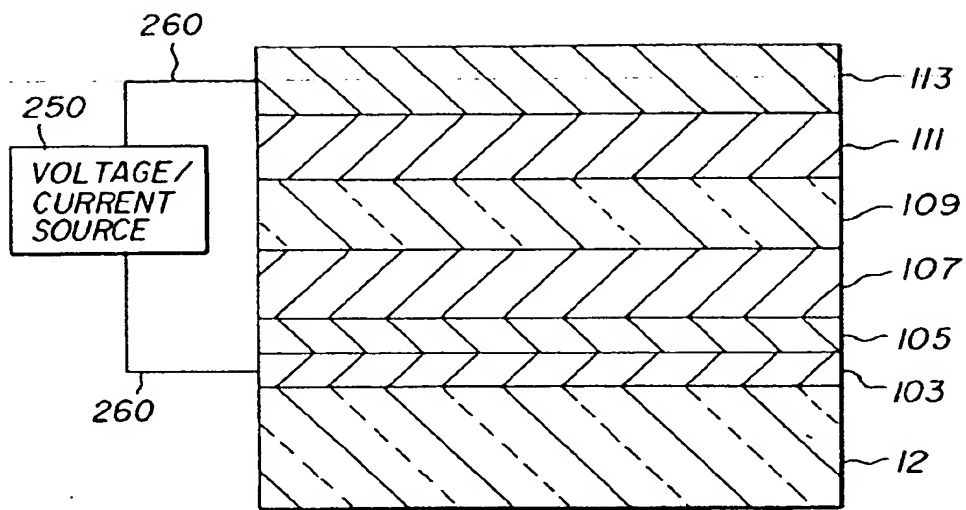


FIG. 6



**FIG. 7**  
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